

AUTOMATION OF SATELLITE OPERATIONS: EXPERIENCES AND FUTURE DIRECTIONS AT NASA GSFC

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ABSTRACT. The programmatic environment for development of spacecraft and their associated ground systems is changing dramatically. Budgets are smaller and there is a strong drive toward more cost-effective operations. This paper describes the current state of satellite operation automation at the NASA Goddard Space Flight Center (GSFC), clarifies where it is heading in the short term, and offers a realistic vision of how automation should be used in future systems. It surveys the current state-of-the-practice in automation of nearly a dozen on-going initiatives and offers insights into the results and hurdles—from system development challenges to social impacts—of each approach. The paper also explores the rapidly evolving level of spacecraft autonomy and how future on-board capabilities will affect ground-based automation efforts. As a conclusion, the authors provide a discussion on the optimal role of automation and some basic principles for automation that can be used to identify favorable opportunities for simplifying or reducing the cost of operating our space-based science missions.

INTRODUCTION

Budgetary reductions, evolving ground system architectures, the increased number and complexity of missions, and the genuine desire to eliminate “business-as-usual,” are all driving the NASA Goddard Space Flight Center (GSFC) to identify more cost-effective approaches for operating scientific spacecraft. Some existing projects are responding by simply automating specific functions that were traditionally performed manually; others are employing a more holistic approach by reengineering the system from end to end. There are numerous research and operational activities that are implementing or have recently deployed automated systems for mission operations. Initial results from these activities are emerging across the spectrum of ground system elements.

The implications of increased spacecraft autonomy, embodied in on-board GPS orbit determination, maneuver control, fault detection and isolation, high level activity planning and execution, and data processing are beginning to have an effect on plans for future systems. It is a true systems engineering challenge to change the flight and ground systems simultaneously in such a way that overall system costs are reduced, especially when separate organizations define requirements and manage the implementation of these two major areas. But this is something that must be done. There are tremendous opportunities to reduce life cycle costs by incorporating new system concepts based on automation and autonomy.

In this paper a distinction is made between automation and autonomy. It is perhaps somewhat artificial, but it helps to clarify the discussion below. Specifically, automation refers to a mode of ground system operation in which manual human actions are not required to accomplish desired functions. Autonomy refers to self-acting, self-regulating systems on the spacecraft wherein functions are delegated to the spacecraft systems.

automation and autonomy running from end to end are rare.

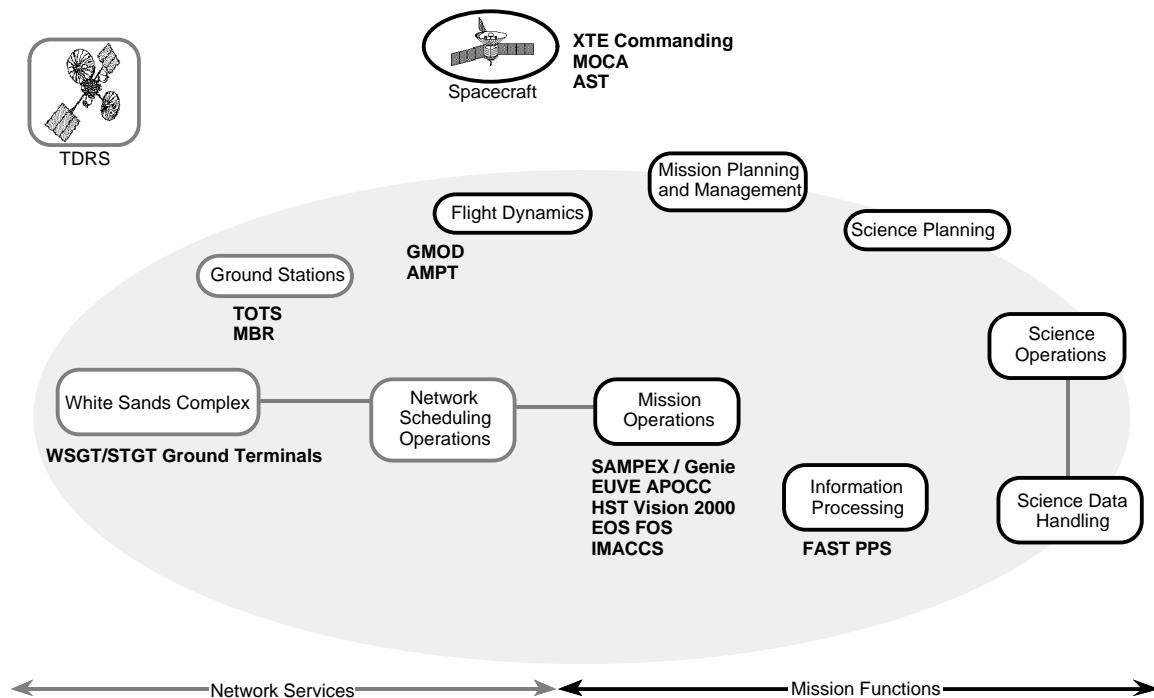


Figure 1. System Context for Automation Initiatives

The following observations and trends of the example activities listed in Table 1 are evident:

- there is a significant number of automation initiatives currently underway at GSFC
- there appears to be insufficient high-level coordination among these activities
- the automation is being retrofitted into existing systems
- the technologies utilized significantly lag the state-of-the-art.
- COTS-based solutions are rare and only recently on the rise
- most activities entail simple incremental improvements of operations through the introduction of automation for discrete functions or tasks
- there is a gradual movement towards a more distributed or, in some rare instances, remotely-controlled system of operations.

Although it is evident that the majority of automation systems are ground-based there has recently been a strong and rapid trend toward the investigation of autonomous functions on-board the

spacecraft. In fact, one project is actively exploring a common space and ground application environment to facilitate the migration of automation functions from ground to space elements. Such a capability coupled with a standard ground-to-space protocol may dramatically influence the manner and efficiency of how we automate and operate our missions. This approach may enable us to better understand the appropriate application, location, and value of automation and autonomy.

In summary, these automation efforts are making good progress toward the goal of more efficient operations. However, the order of magnitude reductions that are desired in operations costs require more than automating islands of activity. These large reductions will require bold changes across the entire end-to-end system.

Table 1. Examples of Automation Projects at Goddard Space Flight Center

Mission & Facility/ Project Name	Characteristics	Status/Notes
GROUND SOLUTIONS		
SAMPEX Mission Operations Center/ Generic Inferential Executor (Genie) & Generic Spacecraft Analyst Assistant (GenSAA) Validation	Automated routine monitoring and commanding (closed-loop control); employs “task-modeling” and increasing levels of automation for acceptance & validation; resulting tools are reusable	Successful demo with live data for over 60 satellite contacts
EUVE Mission Operations Center (MOC) Automated Payload Operations Control Center (APOCC)	“Lights-out” automation of spacecraft operations; notification of remote personnel; FOT involvement in development	Integration into operations autumn ‘96
CGRO MOC/ ROBOT	Automated schedule generation and pass activity management; used end-to-end process flow analysis; FOT participation	Low budget; integration into ops in ‘97
Integrated Monitoring, Analysis, and Control COTS System (IMACCS)	COTS-based ground system; use of state modeling and time-based scripts for pass automation; auto generation of orbit data	Migrating to PC’s and CORBA
EOS Flight Operations Segment	Automated script execution; automated signature/trend analysis; automated failure recovery; remote data access	Development-early stages of design
HST Vision 2000- Monitoring and Analysis	Wide-ranging use of AI and automation techs including neural nets & model-based reasoning to upgrade control center	Development-very complex mission ops
FAST Packet Processing System (PPS)	Fully automated, schedule-driven level zero processing	Operational
White Sands Complex	Fully automated, schedule-driven ground terminal for TDRSS, most failover contingency operations also automated	Operational
GRO Remote Terminal System (GRTS)	Unattended TDRSS ground terminal operations remotely controlled from WSC	Operational
Mila-Bermuda Reengineering	Upgrade of ground network equipment to allow remote control and automation	Development
Transportable Orbital Tracking Station (TOTS)	Fully automated, schedule-driven tracking station with some remote control capability	Operational
ON-BOARD SOLUTIONS		
GPS Modular Software	Modular architecture for GPS autonomous navigation on ground or on orbit	Development- s/c test planned
Automated Maneuver Planning Tool	Automated mission planning and maneuver analysis using fuzzy logic	Development- s/c test planned
XTE Flight Software	Automated on-board attitude and orbit determination supporting autonomous antenna & transponder selection; automated tape recorder management enabling switching of transponders during data dumps	Operational
GPS Payloads and experiments (numerous projects)	Autonomous on-board attitude determination and control; advanced search and acquisition	Many flight experiments

	algorithms	underway
Autonomous Star Tracker (AST)	Autonomous stellar acquisition; attitude solution quaternion output	Development-flight tests planned
Mission Operations Control Architecture (MOCA)	Improved space/ground protocols and application level languages; common application environment for migration of functions from ground to space	Development

FUTURE DIRECTIONS

THE VISION

It is useful to have a guiding vision in discussing how best to use automation and autonomy to get the best payoff in terms of science knowledge per dollar invested in space applications. This vision assumes, extrapolating from experience to date, that much future cost reduction can be derived through an automated ground system coupled with an autonomous spacecraft.

In this vision the principal investigator (PI) and associated staff are the driving force behind all spacecraft operations and the direct recipients of the resulting science data. In short, the PI plans science operations at a workstation. The planning is done graphically through a highly usable interface in terms familiar to the PI. These plans describe science observations and other related activities necessary to accomplish the science goals. Direct real-time control of the payload is possible when desirable.

Once arranged on a timeline, the activities comprise a schedule which is forwarded to the spacecraft through either a local ground-to-space link or through a more centralized communications system. Note that the activities are never transformed into individual commands to slew the spacecraft, activate power supplies, or reposition filter wheels. The activities are in fact a kind of high level language that the spacecraft understands. For example, the spacecraft is told to point at a target and it has systems on board to determine what it must do to prepare for and then execute the appropriate mode changes to slew to the new target and begin an observing sequence.

As observations are made the science data is stored in files on the spacecraft. When the next communication session is scheduled, or when an opportunity presents itself, the files are transferred through the communications network to the PI's computing facility for additional processing and display on the PI's workstation.

The key point is that normal operations involve no human hands touching the system except the PI planning process and the PI data analysis function. All other activities are handled through ground automation and spacecraft autonomy. When anomalies occur there is an on-call team of engineers and operators who can resolve even the most difficult problems. These are the people who developed the spacecraft and ground system and oversaw the launch and early orbit phase of the mission.

IMPLEMENTING THE VISION

At first the vision seems radical. We know that today large sums are spent during mission operations and that the bulk of that money is spent on labor. How can we change so drastically that we eliminate much of that cost? It would be possible to pick a mission and try to implement this vision all at once in order to get the full payoff right now. That is inadvisable, both because of the difficulty of accomplishing so many technical changes at once and because of the large up front investment to develop the new capabilities. Mission PI's are also reluctant to accept the risk and to serve as an "experimental" mission.

A better approach is to rapidly evolve by aggressively introducing a major component of this vision with each mission. There are two axes along which the evolution can take place. Evolution within a mission can be accomplished by gradually increasing automation and autonomy levels during a mission (perhaps during an extended mission when primary science objectives are complete). Along the second axis the baseline varies from one mission to the next, adding a major new element of automation or autonomy with every new mission that launches.

Advances in onboard autonomy allow great simplification and even elimination of functions on the ground. The ground functions which necessarily remain, in the end mostly communication and spacecraft access, are much easier to automate because of their simplicity. Several examples of areas ripe for change are given below.

Further Ground System Automation. It is obvious from the survey of current automation initiatives above that many areas of the ground system are being automated. This trend should continue. While each effort must be judged as an individual business case, many will pass the test and reward the effort with cost savings. Many more control centers can be automated to some extent, at least to the single shift level. Routine operations in all other areas can benefit from automation technology.

However, it becomes apparent quickly that suboptimizing each area does not lead to the overall minimum cost. Changes are required in the end-to-end system. These changes are more difficult to make, but have bigger payoffs.

Elimination of Level Zero Processing. One major change that is relatively straightforward will eliminate much of what is called level zero processing (LZP). LZP is the ground process which takes telemetry data received from the spacecraft and reconstructs the stream of science data. This involves removal of the artifacts which are introduced during space-to-ground communication. The data, typically packets, is put in time order, duplicates are removed, and missing data is noted. This process was required when data was recorded out of order on different parts of an onboard tape recorder and played back in reverse order.

Today's spacecraft have solid-state recorders (SSR). It is now possible to store telemetry data in files on the SSR and/or read data out in the correct order from the SSR to produce the reconstructed science stream on board the spacecraft. With space-to-ground protocols now under consideration, this data can be sent to a ground facility using a file transfer protocol, thereby maintaining both the order and completeness of the data. The analogy with computer file systems and network file transfers is powerful and correct.

Once the files are received on the ground they can be directly distributed to a science computing facility with no further processing. This eliminates the LZP function, saving a substantial amount of funds.

High-level Planning. Much human and computer time is spent dealing with the minute details necessary to make a spacecraft function properly. Today's command sequences contain low-level commands to change the position of each switch, turn power supplies on and off, change the position of filter wheels, accelerate reaction wheels for slewing, and so forth. Everything this sequence of low level commands touches is made more complex and more prone to error.

The level of abstraction throughout the system can be raised by allowing commands to be higher-level, goal-oriented activities. Rather than starting and stopping spacecraft slews by issuing low-level commands to accelerate and decelerate reaction wheels, a new pointing position should be sent to a spacecraft with onboard logic sufficient to execute the complete targeting activity. While this does complicate the spacecraft software somewhat it has benefits throughout the remainder of the system. For instance, once activities are known to be defined correctly, checks are not necessary to ensure a safe upload. All planning and scheduling systems are simplified due to their ability to work with predefined activities common across the system. The low level command management or sequencing function disappears. Sequences of activities can be simulated more easily and quickly. This change is analogous to the change in computer science from assembly language to high-level languages. In essence, we can install a high-level language interpreter on the spacecraft and program it from the planning system.

Flight Dynamics Functions. With the advent of the Global Positioning System (GPS) and other means of accurate onboard orbit determination, it becomes possible for the spacecraft software to know orbits with sufficient accuracy that ground determination and updates are no longer required. This leads directly to the potential for onboard orbit maneuver planning and execution. Techniques are now under development to allow relatively simple artificial intelligence techniques such as fuzzy logic to be applied to maneuver planning. Ground orbit support can become an on-call function with savings in facility and operations costs.

Similar developments in attitude sensors and software will soon allow much of the current ground checking of onboard attitude determination to be reduced or eliminated. Onboard sensor calibration sufficient for many missions will be possible. The elimination of routine ground attitude support will reduce costs while on-call support maintains risk at an appropriate level.

Onboard Fault Detection, Isolation, and Recovery. Today's spacecraft are built with the ability to detect many faults through limit checking and other mechanisms. They can react to a subset of those faults with corrective actions. With faster onboard processors programmed in high-level languages, it is now possible to apply more sophisticated techniques to broaden the range of both detectable faults and responses available. Expert system technology is well understood and is in use in GSFC control centers. Porting an inference engine to an onboard processor should be relatively easy and results in a great gain in functionality. The direct benefit of more onboard capability is less necessity for ground intervention. When the ground system is automated, this is highly desirable.

It is not likely to be economical to try to anticipate and respond to every fault that might occur on a spacecraft; there are just too many possible faults. A better approach is to program an onboard expert system to recognize a core set of basic faults and then over the duration of the mission, add in the faults which occur frequently enough to make the definition process cost-effective. This is also a potential area for migration of functions from the ground to space. New fault detection and recovery logic can be tested on the ground and, when mature, uplinked.

Onboard Science Data Processing. With the increasing power of onboard computers it is possible to do some science processing onboard the spacecraft. Compression, feature extraction, and target of opportunity planning are possible applications. This processing capability can be used to decrease downlink bandwidth and lower response times to interesting phenomena. For missions which are reluctant to forgo raw data, lossless compression is available with appropriate hardware and software onboard and on the ground.

Collaboration Environment. The nature of human support for a mission which is highly automated and autonomous must change. Rather than a continual monitoring role, on-call support is appropriate. However, when anomalies occur, quick responses are sometimes necessary to limit possible further damage. A collaboration environment must be available to the operators and engineers allowing ready access to all needed data from any geographic location. Under certain circumstances, remote control of various system functions may also be desirable.

PRINCIPLES FOR APPLICATION

In reflecting on the changes coming to spacecraft operations, several principles come to mind which can help to guide the way and ensure that the best investment is made in the future.

Spacecraft safety must be maintained.

Regardless of the nature of the automation or autonomy introduced great care must be taken to ensure spacecraft safety. A hierarchical safety net must be maintained which allows graceful degradation of capabilities through longer recovery times. But at the bottom of the safety hierarchy there must be a highly robust safe mode that protects the spacecraft and allows eventual recovery to normal operations.

Reengineer the end-to-end system to get the maximum benefit.

It is easiest to focus on one area of the ground or spacecraft system and optimize its cost-effectiveness. In fact, there can be benefits to that approach. The greatest benefits, however, will come from complementary changes to the ground and flight systems which allow new ways of operating and, in some cases, entire elimination of portions of the current system.

Automation/autonomy investment should be based on business case analysis to be sure that there is a payoff for the investment.

Automation and autonomy should not be introduced as an end in themselves. This technology should be the means to reduce overall system costs or to enable some approach not previously possible. This can be ensured by requiring a business case analysis for each system improvement proposal, focusing a keen eye on the return on investment. Commercial off-the-shelf (COTS) products are one approach to lowering the investment. Amortization across missions is another.

Support the manual phases that remain: spacecraft test, launch and early orbit, and anomaly resolution.

Regardless of how fully automated or how autonomous a mission becomes, manual phases of the mission will remain operator intensive as the system is checked out. Interactive use must be well supported to allow a quick response during critical phases.

Interfaces are key.

As with all system engineering efforts, close attention must be paid to interfaces. Automation and autonomy depend on electronic availability of necessary input data and ready access to all control interfaces necessary to effect desired actions. Adding these after the fact is very costly.

Radical evolution is best.

While it is easy to sit down with a blank sheet of paper and sketch out revolutionary changes to the entire spacecraft and ground system, the result is typically something you cannot afford to build, and even if you had the funding, might very well elude a successful implementation. Our recommended approach might be called radical evolution; that is, only one thread of the end-to-end system is radically changed on a given mission. In a short series of missions, this less risky path can lead to benefits equivalent to that imagined in the start.

Provide insight and access into the automated and autonomous processes.

To better enable operator oversight and possible intervention for unusual or complex situations, it is beneficial to provide a way to closely monitor subtask execution. Such a feature may also prove indispensable for problem resolution. Furthermore, if automation is inserted into operations after a period of manual control, this feature will facilitate validation and acceptance.

Automate as soon in the mission lifecycle as practical.

The decision when to automate may be as important as what or how to automate. Automation clearly can be implemented and integrated at the wrong time. Automation introduced too early may incur unacceptable risk. A delayed decision to automate may limit or prevent access to personnel with the knowledge necessary for success. Delays will also result in limited time to recoup the investment.

Strive for simple solutions.

It is amazing how often this advice is repeated and ignored. Simplicity will benefit both development and end use. Most of the gain comes with the first order solution. Refinements should be shunned when not dictated by true needs.

CONCLUSION

Increased automation and autonomy are one contributor to a robust science program in a time of decreased budgets. Local suboptimization is not the answer. End-to-end systems engineering is. Much progress has been made at GSFC, but much remains to be done. The exciting opportunities discussed above are within reach. We must take advantage of them now.